ACCELEROMETER MEASURED PHYSICAL ACTIVITY AND OBESITY

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ABSTRACT

The use of accelerometers to objectively measure physical activity (PA) volume does not account for inter-individual differences in body mass or cardiorespiratory fitness among adults, which may contribute to the commonly observed discrepancies between objective and subjective measures of PA. Using a sample of 6149 adults from the National Health and Nutrition Survey, the first study demonstrated that for given accelerometer count, individuals with overweight and obesity had a greater rate of energy expenditure than normal weight, and that accounting for differences in energy expenditure due to body mass reduced discrepancies between objective and subjective measures of PA. The second study demonstrated that current accelerometer threshold values used to measure durations of PA may not correspond to the appropriate respective relative intensity of PA after accounting for maximal oxygen consumption by sex and body mass index categories in 828 adults. These results suggest that the established accelerometer thresholds may bias measures of objective PA for individuals with obesity and this may contribute to the discrepancies seen between objective and subjective measures of PA volume.

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LIST OF ABBREVIATIONS

Abbreviation	**Term**
BMI	Body mass index
CPM	Counts per minute
EE	Energy expenditure
MET	Metabolic equivalents
MVPA	Moderate-to-vigorous intensity physical activity
NHANES	National Health and Nutrition Examination Survey
PA	Physical activity
VO_2 max	Maximal oxygen consumption

1.0 GENERAL INTRODUCTION

It is well established that habitual physical activity (PA) participation is associated with positive health outcomes (1), such as improved physical and physiological fitness, and reduced risk of premature death (1,2). For the last several decades, the promotion of PA has been a major part of public health initiatives (3,4). The measurement of PA and the factors that influence it are also important aspects of PA promotion (4). In research and clinical settings, the assessment of PA is useful for monitoring trends in PA and the investigation of associations between PA with health and disease (5). Given that PA is a complex behaviour which consists of several dimensions, including the frequency, intensity, duration, and type of PA such as activities of daily living, active transport, leisure, sports, structured exercise and occupation, measuring PA volume is challenging (6). Nevertheless, it is important to provide an accurate and reliable measurement of PA (4).

PA can be measured using several different tools (6) which fall into two broad categories: subjective and objective measures (6). In large population based studies and interventions, two widely used measures of PA include self-report (subjective) and accelerometers (objective). Although national PA guidelines are primarily based on research using self-reported PA data (7), there is a shift towards the use of accelerometer measured PA (4), even though both measures have been shown to be independently correlated with health-related biomarkers (8). Self-report PA may differ from accelerometer measures factors such as recall bias (6,9,10), social desirability bias (10,11) and individual perception of PA intensity (12), which contribute to the measurement error of self-report. Thus, self-report is generally considered as a less accurate measurement of PA compared to accelerometers (13,14).

Accelerometers capture the changes in velocity over time (accelerations) or activity counts (15,16) and a measure of the duration and frequency of PA, or PA volume (1) at various PA intensities. The higher frequency of accelerations or counts per minute (CPM) indicate higher PA intensity while lower frequencies are reflective of lighter intensity PA (17). The accelerometer intensity thresholds most commonly used are generally the same for all adults, and this approach does not account for individual differences in body mass, sex or cardiorespiratory fitness that may influence the way that accelerometer counts relate to PA volume. Thus, it is important to determine whether the application of equal intensity thresholds within a heterogeneous group contributes to the measurement bias of accelerometer measured PA volume among different sub-groups.

The aim of this current thesis is to provide a greater understanding of how accounting for factors such as body mass and cardiorespiratory fitness will affect the objectively measured durations of PA using accelerometers.

2.0 REVIEW OF RELATED LITERATURE

Introduction

PA can be defined as the movement produced by skeletal muscles which results in energy expenditure (EE) (18). PA consists of several dimensions, such as frequency, type, duration and intensity, and capturing all of these aspects of PA is challenging (6). Subjective and objective tools that are often used to assess PA volume in populations include self-report from questionnaires and accelerometers, which measure the frequency of accelerations (movement) over time (4). However, the current methods used to assess accelerometer measured PA volume, do not account for the individual differences that may impact how accelerometers capture PA. This may contribute to the measurement errors of accelerometers, which are not often examined in the literature.

The following review will discuss the assessment of PA volume using accelerometers and self-report measures. This review will also describe the impact of different accelerometer intensity thresholds on measuring PA volume.

The Assessment of Physical Activity

The assessment of PA volume is an important component of surveillance programs, interventions and public health initiatives (5,17). In research and clinical settings, objective and subjective assessments of PA are useful for investigating trends and associations between PA with health and disease (5). Self-report is the most feasible, and cost effective method to measure PA (5,6) and is a valuable method for providing estimations of the type, duration, and intensity of PA in population-based studies (17). However, self-report is affected by recall bias (6,9,10), social desirability bias (10,11) and individual perception of PA intensity (12,19). Further, individuals tend to over-estimate the duration and frequency of vigorous intensity PA (6,8) and under-estimate the duration and frequency of light-to-moderate intensity PA (6,8). For these reasons, self-report is commonly considered to provide a less accurate measurement of PA compared to objective measures of PA (13,14). The assessment of PA volume using objective measures of PA includes direct observation, indirect calorimetry, doubly labeled water and activity monitors (i.e. accelerometers, pedometers, pulse rate, etc.) (6,20,21). Activity monitors have become increasingly popular in the last couple of decades, which may be attributable to the surge of technological advancements (6,22). The use of accelerometers for assessing PA volume in population-based studies has also increased.

Accelerometers

Accelerometers are small devices that are generally worn on the hip in order to capture free-living PA (23). These devices are able to distinguish between various types of ambulatory activities, such as walking and running (13). They contain sensors that measure linear or angular motions along a single or multiple axes of movement (24). The sensors convert mechanical motions into electrical signals that are proportional to the applied acceleration (25). The signals are then filtered and digitized by converters in the device, and summed over a user-specified period of time (epoch) to provide activity counts per epoch, commonly expressed as CPM (26). Older accelerometer models that are piezoelectric and uni-axial (27–29) only detect dynamic accelerations from motion along one axis (30). Newer models use a capacitive system which is capable of detecting static and dynamic accelerations in two or three axes (31), commonly referred to as bi- or tri-axial accelerometers. There are differences that exist in the filtering process of the signals into activity counts between accelerometer models (17,26,30). Several studies compare the generations of accelerometers for measuring time spent not wearing the accelerometer (non-wear), sedentary, light, moderate and vigorous intensity PA activity, and suggest that tri-axial accelerometers are more accurate than uni-axial accelerometers. However, there are equivocal results regarding the accuracy of accelerometer models, as other studies show no differences between the uses of uni- or tri-axial accelerometers for measuring PA volume (3,32,33). Since becoming commercially available, the uni-axial accelerometer by Actigraph (previously CSA and MTI) model 7164 remains the most commonly used in PA research (3,10,30,34).

Accelerometer placement is important in the assessment of accelerometer validity (3,29,35), reliability (3,35–37), and inter-monitor variability (38,39). Accelerometers can be worn on various locations including the hip (39–42), lower back (40,41), ankle (17,24,25), wrist (25,39,42), thigh (24), chest (24), and arm (24). The investigation of optimal accelerometer placement may be specific to the detection of movement of interest. For example, a study investigating the accuracy of accelerometers for detecting falls found that the chest or waist in combination with the ankle placements provided highest accuracy (43). For the detection of ambulatory movement, previous literature demonstrates that the hip and lower back are practical locations due to their proximity to the center of mass of the body (24,26,30), and provide accurate estimates of activity energy expenditure (EE) (27,38,44).

Predicting Energy Expenditure using Accelerometers

The most common approach used to predict EE from accelerometer data is the conversion of CPM to EE based on the assumption of a linear relationship between the two factors (21). To date, numerous accelerometer validation studies have published EE prediction equations which provide can provide accurate estimates of EE when they are used to evaluate activities that are the same or similar to those from which they were established (45), but may be less accurate for free living activities across a wide range of intensities (46) (47). Other approaches to estimating EE include the use of multiple devices to measure physiological indicators such as heart rate, oxygen consumption and/or accelerations (31,48), artificial neural network models (49,50), decision trees and multiple regression models (51). Newer data processing methods involve machine models, in which computer systems recognize movement patterns and apply algorithms to the accelerometer signal (50) to estimate EE (49,50,52). It is reported that these modelling techniques are able to identify various household and locomotion activities and generate better estimations of EE than the traditional use of CPM thresholds and EE prediction equations (49,50,53). However, these modeling techniques have been mostly applied in independent samples and results from these studies may be limited by the experimental conditions in a highly controlled laboratory data collection setting (50,53). The use of simple EE prediction equations remains the most common method of translating accelerometer data into EE in population studies (45).

Calibration studies typically use oxygen consumption via indirect calorimetry as a criterion measure to demonstrate the relationship between accelerometer CPM and EE during PA (15,17,34,46,54,55). Metabolic Equivalent of Task (MET) values are a ratio of oxygen consumption or EE during activity relative to rest (56). Rest has a value of 1 MET and corresponds to an oxygen consumption of 3.5 milliliters of oxygen per kilogram of body mass per minute ($mL \cdot kg^{-1} \cdot min^{-1}$), or an EE of 1 kilocalorie per kilogram of body mass per hour ($kcal \cdot kg^{-1} \cdot hr^{-1}$)(57). PA intensities are typically classified using a MET of <3 for light intensity, 3-6 for moderate intensity, and >6 for vigorous to maximum intensity (56). However, classification of PA using MET values does not account for the individual perceived effort or relative intensity of that activity (17). For example, walking at a pace of 4.8 $km \cdot h^{-1}$ corresponds to 3 MET and may be perceived as moderate effort for one individual, and vigorous effort for another, depending on their cardiorespiratory and musculoskeletal fitness (58,59). The individual with a higher level of fitness will be performing this activity at a lower relative intensity compared to the individual who is less fit. However, the common classification of MET values by intensity may not accurately estimate EE or activity intensities for individuals who do not have the assumed baseline oxygen consumption rate of $3.5 mL \cdot kg^{-1} \cdot min^{-1}$ (1 MET) (57,60). Indeed, previous literature demonstrates the use of $3.5 mL \cdot kg^{-1} \cdot min^{-1}$ to calculate activity MET causes classification errors of activities, especially for subgroups in populations with low activity and fitness levels (60). As these differences are often overlooked (57), MET values may not appropriately define PA intensity across an adult population (22,55,61).

Accelerometer Intensity Thresholds

Little consensus exist among calibration studies in which the CPM threshold values are established for defining light, moderate, and vigorous PA intensities using absolute MET values (15,55,62)**.** Of the CPM intensity thresholds that have been validated, the most commonly used CPM ranges to define PA intensity include those suggested in 1998 by Freedson et al. (62), using treadmill walking and running in a laboratory setting. They suggest that the common MET values that describe light (1-3 MET), moderate (3-6 MET), and vigorous (6-9 MET) intensity PA correspond to CPM values of 100-1951, 1952 – 5724, and ≥5724 CPM, respectively (62). In 2008, Troiano et al. published a new set of accelerometer intensity thresholds that represent a weighted average of previously validated intensity thresholds, to measure durations of PA for a population. Their ranges were 100-2019 CPM for light (63), 2020-5998 CPM for moderate (8,15,63–65), and ≥5999 CPM for vigorous (15,46,63) intensity PA. These intensity thresholds have since been recommended to be used when analyzing data from large population studies such as the National Health and Nutrition Examination Survey (NHANES) (66). The classification of PA as light, moderate or vigorous intensity will vary depending on the CPM threshold values that are employed (17,67). Further, as the CPM values reflect MET intensity cut-offs, they may or may not be reflective of the relative intensity, particularly as samples from accelerometer validation studies often consist of healthy, young to middle aged participants (46,54,65,67). While validated accelerometer thresholds are representative of PA intensities for the participants in these studies, differences between the study settings, the model of accelerometer used, range of activities used, and participant sample make it challenging to universally apply these intensity thresholds for quantifying the volume of PA in a population (22,65). Despite issues with the generalizability of accelerometer intensity thresholds, which are commonly stated as limitations in the literature (28,62,63,67), durations of PA at the various intensities are often estimated using equal, or universal CPM thresholds for adults (15,68).

The Relationship between Cardiorespiratory Fitness and Accelerometer Counts

Cardiorespiratory fitness levels measured via indirect calorimetry for the determination of maximal oxygen consumption (VO_2 max or VO_2 peak) will vary among individuals of different ages (34,61), sexes (68), and body mass (34). Thus, the relative intensity of PA which is expressed as a percentage of VO_2 max, will differ among individuals with different levels of cardiorespiratory fitness (61). As previously mentioned, for an activity that is equivalent to 3 MET (walking at 4.8 km/h) an individual with a lower level of cardiorespiratory fitness will work at a higher relative intensity with all other things being equal. Using accelerometers, the difference between absolute and relative intensities of PA can be demonstrated in two different ways: 1) The variability in relative PA intensities can be examined for a given accelerometer CPM value, or 2) The variability in accelerometer CPM can be examined at equal relative PA intensities. Several studies demonstrate limitations in applying universal intensity thresholds for subgroups that require more effort to reach the absolute intensities of PA due to their lower cardiorespiratory fitness levels (10,34,68). They conclude that due to the associated declines in cardiorespiratory fitness levels with age and increases in body mass (34,61,68), individuals who are older (68), or have overweight/obesity (10,34) require lower CPM values to reach the given relative intensities that define moderate or vigorous PA intensity (67,68) as compared to individuals with higher levels of cardiorespiratory fitness. Several studies established alternate thresholds for the various PA intensities relative to their specific study samples (ie. older adults, overweight/obese, type 2 diabetes) and suggest the use of specific sub-population thresholds in future accelerometer research (10,67,68). A study conducted by Zisko et al. (68) found that CPM for moderate intensity (46−63 % of VO_2 max) ranged from 669–3367 and 834–4048 CPM and vigorous intensity (64−90 % of VO_2 max) from 1625–4868 and 2012-5423 CPM for older women and men, respectively. Previously, Ozemek et al. (67) found that for individuals across a wide range of cardiorespiratory fitness levels, moderate and vigorous intensity (40 and 60% of heart rate reserve (HRR)) activity the CPM ranged from 1455–7520, and 3459–10066 , respectively. Both of these studies used Actigraph Accelerometer models (GT3X+, and GT1M) which provide comparable CPM values. As with previous validation studies, the prediction equations are useful for determining relative PA intensities at the CPM threshold values and the corresponding absolute PA intensity in MET values.

The Influence of Body Mass on Accelerometer Counts

Using absolute MET values to define accelerometer thresholds may also bias against individuals with overweight or obesity as they would require more energy to move their mass at any given acceleration (Newton's second law: F=ma) (24). Thus, compared to individuals who are normal weight, individuals with overweight or obesity should have higher EE rates for the same PA (34). Additionally, individuals with overweight or obesity also tend to have lower fitness levels compared to individuals who are of normal weight (69), which may make the discrepancies between the intensities represented by CPM intensity thresholds (absolute PA intensity) and the individual effort (relative PA intensity) more pronounced for these individuals (61). However, the use of guideline or universal CPM intensity thresholds across an adult population does not account for individual differences in EE rates at the absolute PA intensities defined by 3 or 6 METs. Thus, measuring PA with guideline thresholds may bias objectively measured PA for individuals with overweight or obesity.

Self-Reported Physical Activity

A frequently used method for measuring PA subjectively includes the self-reporting of PA using questionnaires (17). To date, a multitude of PA questionnaires have been developed, and numerous studies have evaluated their reliability and validity (6,17). Questionnaires vary in their length of recall, the types and details of the questioned asked, and their reliability and validity when compared with objective measures of PA (6,17,70). Although self-report is useful for providing information about PA in a population (6,71), they are limited by the ability of an individual to accurately report PA intensity, frequency and duration (6). Self-report may be affected by personal perceptions of activity intensity (12,72) or social desirability (8,72,73), which may contribute to the over- or under estimation of PA intensity, frequency and/or duration. Nonetheless, questionnaires are commonly used, and this may be due to the ease of their administration, cost-effectiveness, and their ability to provide information about activities that will otherwise not be captured with objective measures (6). For example, accelerometers cannot differentiate between how individual differences in levels of fitness and EE rates during a specific activity will influence the relative intensity of PA, while this can be captured using self-report. Additionally, activities such as swimming, weight training and cycling, will be captured using self-report, but not accelerometers. As self-report and accelerometer measure PA differently, discrepancies between the two measures should be expected. For example, self-report can capture the total or overall duration of activities that involve interval or short bursts of movement interspersed between periods of light or sedentary activity such as volleyball or soccer. While accelerometers will capture intervals or short bursts of movement, they will likely provide much shorter overall durations of PA compared to self-report depending on the epoch length and CPM thresholds used to classify PA intensity. This may contribute to the discrepancies between objective and subjective measures of PA. Over-reporting is often attributed to biases of self-report (63), even though the discrepancies between objective and subjective measures of PA may be due to the limitations of using guideline intensity thresholds to define PA in a population. Studies that measure PA using both self-report and accelerometers in children (12) and adults (72) show that individuals with overweight or obesity tend to have a greater discrepancy between subjective and objectively measured durations of PA compared to individuals who are of normal weight. There are inherent differences between the manner in which components of PA are captured using self-report and accelerometers. This makes the comparison of these two measures challenging, yet it occurs frequently in the literature. For example, the current PA guidelines are largely based on self-report levels of PA (7,74), yet there is an emphasis and growing interest for assessing objective moderate -to- vigorous intensity physical activity (MVPA) in interventions and public health initiatives (17).

Summary of Literature

The relationship between accelerometer CPM and PA intensity may be affected by factors such as age, sex, body mass, and fitness. However, the application of established accelerometer intensity thresholds which describe absolute PA intensities does not account for these factors. This may contribute to the measurement bias of accelerometers for individuals who are not working at the PA intensities described by the accelerometer intensity thresholds. The aim of the current research is to contribute to the understanding of the objective assessment of PA volume using established accelerometer intensity thresholds that are adjusted for body mass and cardiorespiratory fitness in a population. These findings may have important implications for identifying potential measurement bias in how objective PA volume is assessed.

Research Questions:

Study 1

Question 1: How will adjusting the established accelerometer CPM intensity thresholds to correspond to similar EE between BMI categories influence measured PA durations for individuals with overweight or obesity?

Question 2: How will durations of PA estimated using the established and adjusted CPM intensity thresholds compare to self-report PA?

Study 2

Question 1: What relative intensity of PA do the established CPM intensity thresholds correspond to across BMI categories?

Question 2: How will durations of PA estimated using CPM intensity thresholds that account for cardiorespiratory fitness compare with durations of PA estimated using the established CPM intensity thresholds?

3.0 MANUSCRIPT 1

Raiber L, Christensen RAG, Jamnik VK, Kuk JL. Accelerometer Thresholds: Accounting for Body Mass Reduces Discrepancies between Measures of Physical Activity for Individuals with Overweight and Obesity *(Submitted to Applied Physiology, Nutrition, and Metabolism)*

Accelerometer Thresholds: Accounting for Body Mass Reduces Discrepancies between Measures of Physical Activity for Individuals with Overweight and Obesity

Summary 1

Objective: To explore whether accelerometer thresholds that are adjusted to account for differences in body mass influence discrepancies between self-report and accelerometer measured physical activity (PA) volume for individuals with overweight and obesity.

Methods: 6164 adults from 2003-2006 NHANES surveys were analyzed. Established accelerometer thresholds were adjusted to account for differences in body mass to produce a similar energy expenditure (EE) rate as individuals with normal weight. Moderate, vigorous, and moderate-to-vigorous intensity PA (MVPA) durations were measured using established and adjusted accelerometer thresholds and compared to self-report.

Results: Durations of self-report were longer than accelerometer measured MVPA using established thresholds (normal weight: 57.8±2.4 vs 9.0±0.5 min/day, overweight: 56.1±2.7 vs 7.4±0.5 min/day, and obesity: 46.5±2.2 vs 3.7±0.3 min/day). Durations of subjective and objective PA were negatively associated with body mass index (BMI) ($P<0.05$). Using adjusted thresholds increased MVPA durations, and reduced discrepancies between accelerometer and self-report measures for overweight and obese groups by 6.0±0.3 min/day and 17.7±0.8 min/day, respectively ($P<0.05$).

Conclusion: Using accelerometer thresholds that represent equal EE rates across BMI categories reduced the discrepancies between durations of subjective and objective PA for overweight and obese groups. However, accelerometer measured PA generally remained shorter than durations of self-report within all BMI categories. Further research may be necessary to improve analytical approaches when using objective measures of PA for individuals with overweight or obesity.

Introduction

The assessment of physical activity (PA) intensity and volume, which refers to the frequency and duration of PA, are important components of surveillance programs, interventions and public health initiatives (5,17). In research and clinical settings, objective and subjective assessments of PA are useful for investigating trends and associations between PA with health and disease (5). Self-report PA is widely used in population-based studies (17) however, it is not considered as accurate as objectively measured PA (13,14). Accelerometers, which provide an objective measure of PA (6,20), have become increasingly popular in recent decades and are now used for assessing PA in population-based studies (6,22).

Accelerometers capture changes in velocity over time (accelerations) which are known as activity counts (15,16). Thresholds for activity counts per minute (CPM) (15,63) have been created to correspond to Metabolic Equivalents (MET) for moderate (3-6 MET), and vigorous (>6 MET) intensities of PA (56). However, using the same (guideline) CPM intensity threshold values across a heterogeneous population may bias accelerometer measured PA against individuals with greater body mass as they will expend more energy during PA at the same acceleration compared to individuals with a lower body mass (Newton's second law: Force= mass × acceleration) (24).

The differences between accelerometer measured and self-reported durations of PA are often attributed to biases of self-report, and tend to be greater among children (12) and adults (72) with overweight and obesity compared to normal weight. While factors such as body mass, sex, age, ethnicity, sedentary behaviour, and health status may contribute to the discrepancies between accelerometer measured and self-report PA volume, it has been suggested that body mass will likely have the greatest influence on energy expenditure (EE) (75). Whether the discrepancies in between accelerometer measured and self-report PA volume are reduced when using CPM intensity thresholds that account for the difference in EE rates (kcal/hour) among body mass index (BMI) categories is yet to be established. Therefore, the objective of this study is to evaluate how adjustment of established accelerometer CPM intensity thresholds to correspond to similar EE between BMI categories influences measured PA duration. The second objective is to examine how measured PA duration using adjusted thresholds will compare with self-reported PA for individuals with overweight or obesity.

Methods

Data for the current study was obtained from the National Health and Nutrition Examination Survey (NHANES) cycles 2003-2004 and 2005-2006. The NHANES is an ongoing survey which uses a multistage probability design to provide nationally representative data of the United States. Data on demographics, health behaviours, and PA are collected via household interviews (n=20,470) that are followed by health examinations conducted in a mobile examination center (n=19,593). Written informed consent was obtained from participants and study protocol was approved by the National Center for Health Statistics. Complete details of the study design and procedures are reported elsewhere (76).

Participants were excluded from this analysis if they were under 18 years of age (n=8956), classified as underweight (n=3590), were pregnant (n=647), missing self-reported PA (n=4052) or BMI data (n=2834) or had invalid or missing accelerometer data (n=7951). This left 6164 eligible participants.

Data on age (years), sex (male/female), and self-reported PA (minutes/day) were extracted from questionnaires. Body mass and height were measured by trained health technicians using a standardized protocol (77,78). Calculated BMI was used to stratify individuals according to standard cutoffs (79): normal weight (18.5-24.9 kg/m2), overweight (25.0-29.9 kg/m2), and obese (>30 kg/m2).

Self-reported Physical Activity

NHANES includes a questionnaire to assess the mode, frequency, and duration of PA for the 30 days prior to the interview. Moderate and vigorous intensity PA were evaluated with the questions: 1) “Over the past 30 days, did you do moderate activities for at least 10 minutes that caused? only light sweating or a slight to moderate increase in breathing or heart rate?” and 2)

"Over the past 30 days, did you do any vigorous activities for at least 10 minutes that caused heavy sweating, or large increases in breathing or heart rate?" Participants who answered "Yes" to either question were asked to provide the duration and frequency of their activities. To assess active transportation and household/domestic moderate to vigorous physical activity (MVPA), the following two questions were asked: 1) "Over the past 30 days, have you walked or bicycled as part of getting to and from work, or school, or to do errands?" and 2) "Over the past 30 days, did you do any tasks in or around your home or yard for at least 10 minutes that required moderate or greater physical effort?" Participants who answered "Yes" to either question were asked to report the frequency and duration of these activities. Durations of all self-reported PA were summed to derive average minutes of MVPA per day.

Accelerometers

Ambulatory participants were asked to wear a PA monitor on their right hip (Actigraph model 7164, LLC; Ft. Walton Beach, FL) during waking hours for a period of seven days. Only respondents with at least four valid days of wear with >10 hours of wear time per day were used in the analysis. Accelerometer output was classified using established PA intensity thresholds: Light <2020 CPM, Moderate >2020 CPM and Vigorous >5999 CPM (63). Accelerometer measured durations of moderate, vigorous, and MVPA intensities were calculated as the sum of moderate and/or vigorous activity performed in bouts of at least 10 minutes in duration with an allowance of up to 2 minutes below the intensity thresholds (23,63). To be consistent with self-report, accelerometer measured durations of PA were used to derive average minutes per day. The Statistical Analysis System (SAS) syntax used to calculate PA volume is available at: http://www.cdc.gov/nchs/tutorials/PhysicalActivity/Downloads/downloads.htm (80). Additional details of the NHANES accelerometer protocol have been previously described elsewhere (15).

Energy Expenditure Prediction Equations

At the established moderate (2020 CPM or 3 MET) and vigorous (5999 CPM, or 6 MET) PA intensity thresholds, four validated generalized EE prediction equations (28,39,41,62) were used to calculate gross MET values and EE rates across the BMI categories. Resting metabolic rate (1 MET) was subtracted from the derived gross MET values, and then multiplied by the mean body mass of each BMI category to obtain activity EE (kcal/hour; assuming 1MET = 1 kcal/kg/hour) at the moderate and vigorous CPM intensity thresholds. The net EE rates of the normal weight group at the established CPM intensity thresholds were then used to derive new CPM intensity thresholds for overweight and obese groups using their respective mean body masses. As such, the calculated BMI-specific CPM intensity thresholds resulted in similar EE rates for all BMI classes. The following prediction equations were used to determine new CPM intensity thresholds for overweight and obese individuals:

1) **Freedson et al.:** MET = 1.439008 + (0.000795·CPM)
2) **Hendelman et al.:** MET = 1.602 + (0.000638·CPM)
3) **Swartz et al.:** MET = 2.606 + (0.0006863·CPM)
4) **Yngve et al.:** MET = 0.751 + (0.0008198·CPM)

New CPM intensity thresholds for moderate and vigorous intensity were used to calculate durations of moderate, vigorous, and MVPA for overweight and obese groups, which were then compared with self-reported durations of PA.

Data Analysis

Continuous variables are reported as mean ± SE and categorical as frequency and prevalence. Group differences for characteristics by BMI category, and durations of PA at all intensities were assessed using one-way analysis of variance tests for continuous variables, and chi-square tests for the categorical variable. Differences between measured durations of PA calculated by the different equations and between measured and self-reported durations of PA within BMI categories were assessed using repeated measures analysis of variance with least-squared differences *post hoc* comparisons tests. All statistical analyses were conducted using SAS v9.4 survey procedures and weighted to provide results representative of the U.S population. Statistical significance was considered at $P < 0.05$.

Results

Participant characteristics and physical activity durations by BMI category are presented in **Table 1**. Self-reported durations of PA in all BMI categories were significantly longer than accelerometer measured PA using the established thresholds ($P<0.05$). In general, durations of self-reported and measured PA were shorter with increasing BMI. The absolute difference between durations of accelerometer measured and self-report moderate PA intensity were similar across the BMI categories, and the absolute differences between durations of accelerometer measured and self-report vigorous intensity and MVPA were significantly lower among those with obesity compared to normal and overweight groups.

New calculated intensity thresholds and PA durations

EE rates for each BMI category were calculated using the Freedson, Hendelman, Swartz and Yngve prediction equations using the mean body mass of the respective BMI groups (**Table 2**). EE rates at established moderate and vigorous intensity thresholds were significantly higher with increasing BMI (**Table 2**, $P<0.05$). New CPM intensity thresholds were calculated to represent the CPM required for groups with overweight and obesity to reach similar activity EE rates as the normal weight group (referent), at moderate (3 MET) and vigorous (6 MET) intensity (**Table 3**). The durations of MVPA using the adjusted thresholds for the overweight and obesity groups were significantly different between all the equations within each BMI class ($P<0.05$) and were significantly longer with new intensity thresholds as compared to established thresholds ($P<0.05$) but generally remained shorter than self-report values (**Figure 1**). Within the overweight and obesity groups, the Swartz adjusted thresholds produced significantly longer durations of MVPA than the other equations and self-report values ($P<0.05$).

Between BMI groups, the new thresholds still generally resulted in shorter MVPA durations for individuals with obesity as compared to normal weight ($P<0.05$). The only exception was when using the Yngve adjusted thresholds that resulted in MVPA durations that were not significantly different between the between the normal weight with the overweight ($P=0.13$), and obesity groups ($P=0.55$).

Discussion

Findings from this study suggest that using a single established accelerometer CPM intensity threshold may bias measures of PA durations for individuals with overweight or obesity as compared to normal weight. When accelerometer CPM intensity thresholds were adjusted for differences in body mass among BMI categories, the discrepancies between accelerometer measured and self-reported PA volume were reduced for individuals with overweight or obesity. Therefore, additional research is needed to clarify whether population-specific accelerometer thresholds are needed to evaluate PA volume.

The current approach of applying guideline CPM thresholds for quantifying moderate (2020 CPM or 3 MET) and vigorous (5999 CPM or 6 MET) intensity PA (63) does not account for differences between individuals that may influence PA intensity and how it relates with CPM. Indeed, individuals with greater body mass require more energy (greater force) to achieve the same acceleration or movement compared to individuals who are normal weight. For example, at an equal walking pace, individuals with obesity will expend more energy than individuals who are normal weight (81), yet accelerometers capture similar CPM (82). Additionally, the guideline CPM thresholds that correspond to 3 and 6 MET using the standard reference of a healthy 65kg male (56), do not account for the differences in aerobic and musculoskeletal fitness among individuals (10,61,67,68,83,84). Thus, at a given absolute intensity of PA (ie. 3 or 6 MET), individuals with a lower aerobic fitness will experience higher relative intensity of PA compared to those who with a higher level of aerobic fitness (69). As individuals with overweight and obesity are more likely to have a low fitness (67), in conjunction with their higher body mass, they will need to work at even higher relative intensities at the guideline accelerometer CPM threshold values. As such, PA volume may be under-estimated for individuals with overweight or obesity. Indeed, small studies demonstrate that individuals with overweight or obesity (10,34)and the elderly (68) work at a higher relative intensity than described by the commonly used definitions of 3 and 6 MET when asked to engage in PA that would measure the same accelerometer CPM values as normal weight and younger populations. In the current study, we demonstrate that at the established accelerometer CPM intensity thresholds the calculated EE rates were significantly greater with increasing obesity. When the accelerometer CPM intensity thresholds were adjusted to result in equal EE rates among all BMI categories, individuals with overweight and obesity required lower accelerometer CPM values to describe moderate and vigorous intensity PA.

Currently, it is unclear what accelerometer CPM intensity threshold values should be used to more appropriately assess PA volume in various sub-populations. Studies that examine various populations with different fitness levels based on body mass, age and sex report ranges of accelerometer CPM values for moderate intensity PA between 669 and 7520 CPM (67,68). In the current study, the adjusted MVPA intensity threshold values generally fall within the lower range of the previously published thresholds, with only the Swartz equation falling below this range. Nevertheless, this extremely large range suggests that there may not be a single appropriate threshold value to define PA intensity in a heterogeneous population. The choice of accelerometer CPM intensity threshold values to appropriately represent relative PA of individuals or groups within a population remains a challenge as the validation of accelerometer CPM threshold values are influenced by population characteristics, the accelerometer used and the ranges of activities performed. Clearly more work is needed to verify the findings here to determine the most optimal balance between the ease of using a single threshold versus the accuracy of multiple population-specific thresholds.

Both accelerometers and self-report are used to assess PA volume. However, the PA durations reported by each method are generally very different and this likely due to the differences in how they capture PA. Accelerometers are considered a valuable tool for the assessment of ambulatory movement, but are unable to capture activity such as those involving the upper extremities (20), weight training (22,41), cycling or swimming (20,37,39), which are captured in self-report. Further, activities that involve interval or short bursts of movement interspersed between larger periods of light or sedentary activity such as volleyball or soccer, would likely be captured by accelerometers as a much shorter overall duration as compared to the self-reported values. This may contribute to the shorter durations of PA commonly measured by accelerometers. Indeed, self-reported durations of PA were greater than measured for all BMI groups. Further, there are differences in the types of PA that different BMI groups engage in. For example, a study suggests that individuals with overweight or obesity report that they are more likely to engage in swimming (85) which will not be captured by accelerometers. Given the differences that exist between the ways in which PA volume is captured using self-report and accelerometers, the comparison these two measures is challenging, yet it occurs frequently in the literature. While the measurement of PA using accelerometers and self-report both have their own inherent limitations (65), the discrepancies between these measurements are often attributed to errors in self-report (63). Individuals with overweight or obesity are reported to be more affected by factors such as social desirability, and weight stigma thereby further contributing to the over-estimation of moderate to vigorous PA (6,19) durations using questionnaires (6). However, the over-estimation of PA durations measured in a questionnaire may be due to individuals under-estimating the intensity of PA that are described as MVPA (19). Previous literature commonly states that over-reporting is more prevalent among individuals with obesity

(12,20,32,72,73,83,84). However, our results suggest that the over-reporting trends could be due to the bias of the accelerometer measurement of PA volume for individuals with obesity. In fact, after accounting for the higher body mass of individuals with obesity, durations of MVPA was increased by 3 to 17 min/day depending on the equation used. This magnitude of difference is likely relevant given that even 10 minutes of MVPA is associated with positive health effects (65). Surprisingly, using the Swartz adjusted thresholds we observed that durations of accelerometer measured MVPA for individuals with obesity were increased by more than 80min/day as compared to the established CPM thresholds, and were almost 2 times longer than self-report values. This difference may be in part because the Swartz study used fewer ambulatory activities as compared to the other studies, and thus the EE for a given CPM predicted tended to be higher. Thus, more work may be needed to clarify the relationship between EE and CPM, particularly in populations with overweight or obesity.

Several limitations exist in the current study. It is unclear whether the discrepancies observed between MVPA durations as assessed by accelerometer and self-report are due to the ability of self-report to capture a wider scope of activities than accelerometers (ie. swimming, cycling, resistance training, etc.) or due to issues with self-report such as report bias or methodological issues in the way questions were asked resulting in double counting or activities that were missed. The EE prediction equations used in this study are widely used, but were created and validated with predominantly healthy and normal weight participants (28,39,41,62), and may not be generalizable for individuals with overweight or obesity. However, to our knowledge, valid energy prediction equations derived specifically for individuals with overweight and obesity do not exist. The strength of this study is the use of a nationally representative sample of the civilian adult population in the United States.

In summary, the use of alternate accelerometer CPM intensity thresholds that account for differences in EE due to body mass reduced the discrepancies between accelerometer and self-reported durations of PA for individuals with overweight and obesity. As the guideline intensity thresholds correspond to higher rates of EE for overweight and obese groups, they may inappropriately bias accelerometer measured PA in individuals with overweight or obesity. As such, further research may be required to determine whether the improvements gained in accounting for obesity status or other factors such as age, physical activity patterns or aerobic fitness warrant the creation of population-specific CPM thresholds.

Table 1: Participant characteristics by body mass index category

	Normal Weight	Overweight	Obese
Sample size (n)	1960	2209	1995
Age (years)	45.2 ± 0.6	50.0 ± 0.6*	48.6 ± 0.5*†
Sex (n, % Male)	937 (47.8)	1314 (59.5)*	917(46.0) *†
BMI (kg/m^2)	22.5 ± 0.0	27.4 ± 0.0*	35.4 ± 0.2*†
Self-Reported PA (min/day)			
Leisure Time Moderate Intensity	20.2 ± 1.3	19.1± 0.8	16.2 ± 0.9*†
Leisure Time Vigorous Intensity	12.9 ± 0.8	9.1 ± 0.6*	5.6 ± 0.4*†
Total MVPA	57.8 ± 2.4	56.1 ± 2.7	46.5 ± 2.2*†
Accelerometer measured PA (min/day)			
Moderate intensity	7.1 ± 0.4‡	6.3± 0.4‡	3.5± 0.2*†‡
Vigorous intensity	0.9 ± 0.1‡	0.6± 0.1*‡	0.1± 0.0*†‡
Total MVPA	9.0 ± 0.5‡	7.4 ± 0.5*‡	3.7 ± 0.3*†‡

Values are presented as mean ± SE.

* = Statistically different from normal weight group (P<0.05)
† = Statistically different from overweight group (P<0.05)
‡ = Statistically different from self-report (P<0.05)

Table 2: Energy expenditure rates calculated using common prediction equations by body mass index category

	Normal Weight	Overweight	Obese
Body mass, BM (kg)	64.1 ± 0.3	79.5 ± 0.2*	101.0 ± 0.7* †
EE rate at 2020 CPM (kcal/hour)			
Freedson MET = 1.439008 + (0.000795·CPM)	131 ± 1	163 ± 0*	206 ± 1* †
Hendelman MET = 1.602 + (0.000638·CPM)	121 ± 1	150 ± 0*	191 ± 1* †
Swartz MET = 2.606 + (0.0006863·CPM)	192 ± 1	237 ± 1*	302 ± 2* †
Yngve MET = 0.751 + (0.0008198·CPM)	90 ± 0	112 ± 0*	142 ± 1* †
EE rate at 5999 CPM (kcal/hour)			
Freedson MET = 1.439008 + (0.000795·CPM)	334 ± 2	414 ± 1*	526 ± 4* †
Hendelman MET = 1.602 + (0.000638·CPM)	284 ± 1	353 ± 1*	448 ± 3* †
Swartz MET = 2.606 + (0.0006863·CPM)	367 ± 2	455 ± 1*	578 ± 4*†
Yngve MET = 0.751 + (0.0008198·CPM)	299 ± 2	371 ± 1*	471 ± 3* †

Values are presented as mean ± SE.
* = Statistically different from normal weight group ($P<0.05$)
† = Statistically different from overweight group ($P<0.05$)

Table 3: New CPM intensity threshold calculations using common prediction equations by body mass index category

	Normal Weight	**Overweight**	**Obese**
Moderate Intensity CPM Thresholds*			
Freedson: CPM= (131/BM – 0.439008) /0.000795	2020	1522	1081
Hendelman: CPM= (121/BM – 0.602) /0.0006389	2020	1446	939
Swartz: CPM= (192/BM – 1.606) /0.0006863	2020	1175	428
Yngve: CPM =(90/BM + 0.249) /0.0008199	2020	1687	1393
Vigorous Intensity CPM Thresholds*			
Freedson: CPM= (334/BM – 0.439008) /0.000795	5999	4729	3607
Hendelman: CPM= (284/BM – 0.602) /0.0006389	5999	4653	3464
Swartz: CPM= (367/BM – 1.606) /0.0006863	5999	4382	2954
Yngve: CPM = (299/BM + 0.249) /0.0008199	5999	4894	3918

*New threshold calculations include adjustment for resting metabolic rate (1MET).

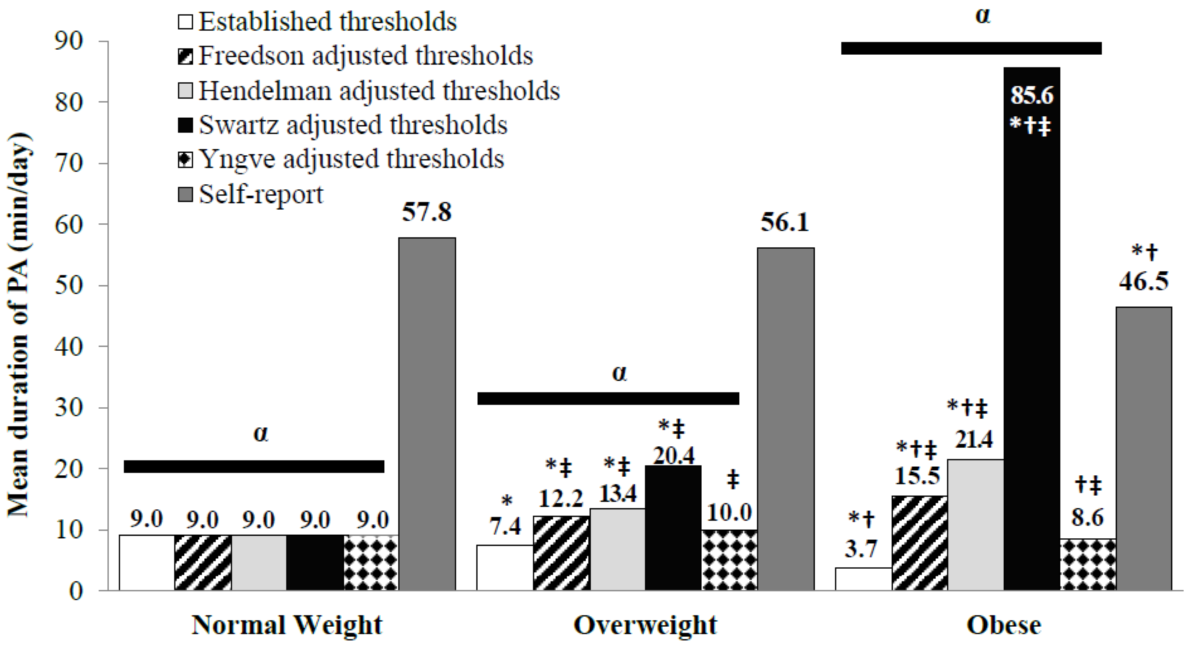


Figure 1. Durations of measured and self-reported moderate to vigorous physical activity by body mass index category

Durations of MVPA between adjusted thresholds are statistically different within overweight and obesity groups.

* = Statistically different from normal weight group (P<0.05)
† = Statistically different from overweight group (P<0.05)
‡ = Statistically different from established thresholds (P<0.05)
α = Statistically different from self-report (P<0.05)

4.0 MANUSCRIPT 2

Raiber L, Christensen RAG, Jamnik VK, Kuk JL. Do Moderate to Vigorous Intensity Accelerometer Count Thresholds Correspond to Relative Moderate to Vigorous Intensity Physical Activity?

Do Moderate to Vigorous Intensity Accelerometer Count Thresholds Correspond to Relative Moderate to Vigorous Intensity Physical Activity?

Summary 2

Introduction: The established accelerometer intensity thresholds do not account for individual differences in cardiorespiratory fitness (VO_2 max). Thus, PA volume may be under-estimated for individuals with obesity who tend to have lower VO_2 max. This study aims to predict %VO_2 max at established accelerometer intensity thresholds, estimate and compare durations of objective PA among individuals in different BMI categories.

Methods: 828 adults from NHANES 2003-2004 were analyzed. MET values using established accelerometer intensity thresholds were converted to %VO_2 max. Next, accelerometer counts corresponding to 40 and 60% of VO_2 max by sex and BMI category were also determined.

Results: Relative intensity was under-estimated at the established accelerometer intensity thresholds for all adults; however individuals with overweight and obesity work at significantly higher %VO_2 max compared to normal weight due to lower fitness. Thus, individuals with overweight and obesity require significantly lower accelerometer counts to reach relative moderate and vigorous PA intensities (40 and 60% VO_2 max) compared to normal weight. Using these new thresholds, durations of MVPA were shorter compared to the established thresholds (Yngve: 2.2±0.5, Swartz: 5.9±0.7, Hendelman: 2.4±0.5, Freedson: 3.3±0.6 min/day, vs Established: 9.4±1.0 min/day, $P<0.05$), and remained shorter among individuals with obesity compared to normal weight ($P<0.05$). Regardless of the intensity thresholds used, a greater proportion of individuals with normal weight met the PA guidelines of 150 min/week for MVPA compared to individuals with obesity ($P<0.05$).

Conclusion: As the established MVPA CPM intensity threshold corresponds to < %20 of VO_2 max for all BMI categories, accelerometer measured PA volume may be over-estimated. More

work may be needed to improve the methods used for accelerometer measured PA in the population.

Introduction

In research and clinical settings**,** the assessment of physical activity (PA) is important for monitoring the frequency, duration and intensity of PA on health and disease management outcomes (5)**.** The volume, which commonly refers to the duration and frequency of PA required to positively influence health and disease outcomes acutely and chronically may be achieved through any combination of duration and frequency of PA at a specific intensity that considers the unique needs plus physical and physiological attributes of the individual (17).

Accelerometers are commonly used for objectively measuring PA volume in research studies (6,22)**.** Accelerometers capture changes in velocity over time (accelerations) or activity counts per minute (CPM) (15,16). Several validations studies have produced energy expenditure (EE) prediction equations to provide a method for converting CPM to absolute EE in METs, and identify CPM intensity thresholds that denote moderate and vigorous intensities of PA (28,39,41,46,62). However, using a single universal CPM threshold value to denote light or moderate or vigorous PA intensities does not account for the individual differences in cardiorespiratory fitness or maximal oxygen consumption (VO_2 max) on the perceived or relative intensity (%VO_2 max) of PA. Thus, the relative intensity of PA will be under-estimated in populations with lower levels of cardiorespiratory fitness, such as those with obesity. This may contribute to the larger magnitude of over-reporting of PA commonly observed among individuals with overweight and obesity (12). As such, the purpose of this study is two-fold: 1) to predict the relative intensity of PA that corresponds to established CPM intensity thresholds across the standard body mass index (BMI) categories ; and 2) to estimate and compare durations of objectively measured PA using established and new CPM intensity thresholds based on cardiorespiratory fitness.

Methods

Data for the current study was obtained from the National Health and Nutrition Examination Survey (NHANES) 2003-2004 study cycle as this was the only survey year in which objectively measured PA and fitness testing data were collected. The NHANES is an ongoing survey which uses a multistage probability design to provide nationally representative data of the United States. Data on demographics, health behaviours, and PA are collected via household interviews and followed by health examinations conducted in a mobile examination center. Written informed consent was obtained from participants and the study protocol was approved by the National Center for Health Statistics. Complete details of the study design and procedures are reported elsewhere (76).

A total of 10,122 participants were examined in this study cycle. Participants were excluded from the analysis if they were under 18 years of age (n=4502), pregnant (n=292), classified as underweight (BMI < 18.5 kg·m^2, n=3102), missing estimated VO_2 max (n=7313), self-reported PA (n=2887), or BMI (n=1435) or had invalid or missing accelerometer data (n=5268). The resultant analyses were conducted on 828 individuals.

Age, sex, and self-reported PA (minutes/day) were extracted from questionnaires. Body mass and height were measured by trained health technicians using a standardized protocol (77,78). Calculated BMI was stratified according to standard categories (79): normal weight (18.5-24.9 kg·m^2), overweight (25.0-29.9 kg·m^2), and obesity ($\geq$30 kg·m^2).

Self-Reported Physical Activity

NHANES includes a questionnaire to assess the mode, frequency, and duration of PA for the 30 days prior to the interview. Moderate and vigorous intensity PA were evaluated with the questions: 1) “Over the past 30 days, did you do moderate activities for at least 10 minutes that caused? only light sweating or a slight to moderate increase in breathing or heart rate?" and 2) "Over the past 30 days, did you do any vigorous activities for at least 10 minutes that caused heavy sweating, or large increases in breathing or heart rate?" Participants who answered "Yes" to either question were asked to provide the duration and frequency of their activities. To assess active transportation and household/domestic moderate to vigorous physical activity (MVPA), the following two questions were asked: 1) "Over the past 30 days, have you walked or bicycled as part of getting to and from work, or school, or to do errands?" and 2) "Over the past 30 days, did you do any tasks in or around your home or yard for at least 10 minutes that required moderate or greater physical effort?" Participants who answered "Yes" to either question were asked to report the frequency and duration of these activities. Durations of self-report PA were summed to derive average minutes per day.

Accelerometers

Ambulatory participants were asked to wear a PA monitor on their right hip (Actigraph model 7164, LLC; Ft. Walton Beach, FL) during waking hours for a period of seven consecutive days. Only respondents with at least four valid days of wear with ≥10 hours of wear time per day were used in the analysis. Accelerometer output was classified using established PA intensity thresholds: Light <2020 CPM, Moderate≥2020 CPM and Vigorous ≥5999 CPM (63). To be consistent with the self-reported PA questionnaire data, accelerometer measured durations of moderate, vigorous, and MVPA intensities were calculated as the sum of moderate and/or vigorous activity bouts of at least 10 minutes in duration with an allowance of up to 2 minutes below the intensity thresholds to be consistent with previous accelerometer literature (23,63). To be consistent with the self-report volume of PA data, accelerometer durations of PA were used to derive average minutes per day. The Statistical Analysis Software (SAS) syntax used to calculate

PA volume is available at:

http://www.cdc.gov/nchs/tutorials/PhysicalActivity/Downloads/downloads.htm (80). Additional details of the NHANES accelerometer protocol have been previously described elsewhere (15).

Maximal Oxygen Consumption

Participants performed a submaximal exercise test conducted by trained health technicians. They were assigned one of eight treadmill protocols based on their sex, age, BMI, and self-reported PA (86). All protocols included a 2-min warm up, two 3-min exercise stages, and a 2-min cool down. Estimated VO_2 max values at age predicted HR max were extrapolated assuming a linear relationship between heart rate and oxygen consumption during exercise (87). A more detailed description of the 2003-2004 NHANES fitness test procedures and protocols can be found elsewhere (66).

Established and New Calculated Intensity Thresholds

Four (28,39,41,62) EE prediction equations were used to calculate MET values at the established intensity thresholds for moderate (2020 CPM) and vigorous (5999 CPM) intensity PA by sex and BMI categories:

1) **Freedson et al.:** MET = 1.439008 + (0.000795·CPM)

2) **Hendelman et al.:** MET = 1.602 + (0.000638·CPM)

3) **Swartz et al.:** MET = 2.606 + (0.0006863·CPM)

4) **Yngve et al.:** MET = 0.751 + (0.0008198·CPM)

MET values were converted to absolute oxygen uptake (VO_2; assuming 1 MET = 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$) and then expressed relative to the estimated VO_2 max (% VO_2 max). Next, the reverse process was undertaken to determine the mean CPM values which correspond to the commonly used %VO_2max thresholds for moderate (40% VO_2 max) and vigorous (60% VO_2

max) intensity (88). New and established CPM intensity thresholds were then used to estimate durations of objectively measured PA.

Data Analysis

Continuous variables were reported as mean ± standard error and categorical variables were reported as prevalence ± percent standard error. Differences in demographics and PA variables by BMI category and sex were assessed using one-way analysis of variance tests for continuous variables, and chi-square tests for the categorical variables. Differences between established and calculated relative intensities (%VO_2 max) and accelerometer CPM values, and between objective and subjective durations of PA within BMI categories and sex were assessed using repeated measures analysis of variance with least-squared differences *post hoc* comparisons tests. All statistical analyses were conducted using SAS v9.4 survey procedures and weighted to provide results representative of the U.S population. Statistical significance was considered at $P < 0.05$.

Results

Participant characteristics and durations of objective and subjective PA by BMI category and sex are presented in **Tables 1** and **2**, respectively. Cardiorespiratory fitness (estimated VO_2 max) was lower among individuals with overweight and obesity compared to those with normal weight ($P<0.05$), and in women compared to men ($P<0.05$). Cardiorespiratory fitness did not differ between the overweight and obese categories for both men and women ($P< 0.05$). Durations of accelerometer measured MVPA using the established and new CPM thresholds were shorter than self-report MVPA for all BMI categories and both sexes ($P<0.05$). Further, self-report and objectively measured MVPA tended to be shorter among individuals with obesity compared to normal weight using the established accelerometer CPM thresholds (**Table 2**). Thus, a greater proportion of men and women with normal weight met the PA guidelines of 150 min per week for MVPA compared to individuals with obesity using self-report (72 vs 60%) or objectively measured PA (23 vs 10%).

Relative intensity of PA at established accelerometer thresholds

The % VO_2 max (relative intensity) corresponding to the established 2020 (moderate intensity) and 5999 (vigorous intensity) CPM were calculated using the four prediction equations (**Table 3**). Regardless of the equation used, individuals with overweight and obesity had a significantly higher predicted % VO_2 max at 2020 and 5999 CPM compared with those with normal weight ($P<0.05$), with women having higher predicted % VO_2 max compared to men ($P<0.05$).

New calculated intensity thresholds

CPM that correspond to 40% (moderate intensity) and 60% (vigorous intensity) of VO_2 max by sex and BMI category were calculated **(Figure 1)**. Depending on the prediction equation used, the new CPM intensity thresholds were generally greater than the established intensity thresholds within all BMI categories and both sexes. Further, the new CPM intensity thresholds were significantly lower for individuals with overweight or obesity compared to normal weight for both sexes ($P<0.05$), and were lower for women compared to men ($P<0.05$).

Mean durations of MVPA for all BMI categories estimated with new intensity thresholds were significantly shorter than durations of PA estimated using established thresholds (Established: 9.4±1.0 min/day vs Yngve: 2.2 ± 0.5, Swartz: 5.9±0.7, Hendelman: 2.4±0.5, Freedson: 3.3±0.6 min/day). Using the new CPM intensity thresholds, less than 10% individuals met the guidelines of 150 min per week of PA, with a greater proportion of individuals with normal weight and overweight meeting the guidelines as compared to those with obesity (normal weight: 10%, overweight: 10%, obesity: 6%). In fact, on average, less than half of the U.S. population achieved even one minute of MVPA (Normal weight: 52%, overweight: 52%, obesity: 41%).

Discussion

This study suggests that the established moderate and vigorous intensity CPM thresholds may be associated with lower than expected relative intensity values after accounting for cardiorespiratory fitness levels in the U.S population. When CPM intensity thresholds were corrected to correspond to 40 and 60% of VO_2 max for moderate and vigorous intensity, durations of accelerometer measured PA were even shorter than using the established intensity thresholds for all BMI categories and sexes. In fact, the CPM thresholds currently used were the most under-estimated for individuals with normal weight. Thus, the greater discrepancies between subjective and objective PA in individuals with obesity compared to objective measures may be in part due to methodological issues associated with using a single universal CPM intensity threshold. Thus, more research is needed to clarify the best approach for assessing PA volume on a population level using accelerometers.

Previous validation studies demonstrate that the EE is accurately predicted by accelerometers (28,39,41,62). Some studies report that these equations may substantially misclassify PA intensity in free-living settings (45,89). A review by Lyden et al. (45) concludes that the Actigraph MET prediction equations under-estimate EE 72% of the time. Similarly, they report a prediction bias of -1.4 MET for the Freedson equation, and -0.6 MET for the Swartz equation across all activities. Conversely, the Hendelman (90) and Yngve (41) equations are reported to overestimate EE at light and moderate intensity PA. These studies are often conducted in laboratory settings, using specific activities and small samples which consist of predominately young, healthy and normal weight populations which may limit their generalizability (42,46,91). Within our study, even the relative intensity estimated for individuals with normal weight at the established CPM threshold (12-19% of VO_2 max) was substantially lower than the common definition of 40% of VO_2 max for moderate intensity. Further, the discrepancies between the established and newly calculated CPM values associated with moderate and vigorous relative intensity were even greater for individuals with normal weight than for individuals with overweight or obesity. Thus, future research is needed to better understand how to best translate CPM values into PA intensity.

For a given absolute intensity of PA, individuals with a lower level of cardiorespiratory fitness will experience higher relative intensity of PA compared to those with a higher level of fitness (69). This means that individuals with overweight and obesity, who tend to have lower levels of cardiorespiratory fitness (67) are more likely to work at higher intensities of PA than individuals with normal body weight at the same CPM value. Thus, using single universal CPM values and not accounting for the inter-individual differences in cardiorespiratory fitness levels in a population (10,61,67,68,83,84) will bias PA assessment against populations with lower cardiorespiratory fitness levels**.** In the current study, accounting for differences in VO_2 max led to substantially lower predicted CPM intensity thresholds for individuals with overweight and obesity than individuals with normal weight. Similarly, previous studies have reported lower CPM thresholds ranges for moderate intensity PA ranging between 669 and 7520 CPM (67,68) in populations with different ages (61), body masses (10,34), and cardiorespiratory fitness levels (67,68). However, the advantages gained in predication accuracy for surveillance and examination of the association between PA and health need to be balanced with the clinical feasibility of using and developing multiple population-specific CPM intensity thresholds.

Durations of PA achieved will depend on the intensity CPM threshold value used (10,92). Lower moderate intensity CPM threshold values will result in longer durations of measured PA. Conversely, using a higher moderate intensity CPM threshold values will mean that more PA would not qualify as moderate intensity PA, resulting in shorter durations of PA. It is suggested that adults with overweight and obesity tend to over-report PA and engage in less MVPA compared to normal weight (12,20,32,72,83,84). However, as the methods for objectively assessing MVPA in populations often use a one-size-fits-all approach, they may be biased against individuals with lower levels of cardiorespiratory fitness, such as those with overweight or obesity. Accounting for cardiorespiratory fitness reduced the magnitude of difference in objective PA duration between the BMI categories. Nonetheless, durations of objective PA remained shorter for individual with obesity than normal weight across all PA Intensities. While accounting for cardiorespiratory fitness may improve the measurement errors associated with assessing PA with accelerometers, large discrepancies remained between durations of objective and subjective PA for both sexes across all BMI categories. With current PA guidelines being largely based on self-report levels of PA, and emphasis and growing interest for assessing objective MVPA in interventions and public health initiatives, more research is needed to improve the comparability of objective and subjective measures of PA.

Several strengths and limitations exist in the current study. The NHANES provides direct measures on a nationally representative sample of the civilian adult population in the United States. Although a sub-maximal exercise provided estimated measures that are strongly associated with measured maximal oxygen consumption (93), errors exist. Additionally, the exclusion of individuals who did not complete the NHANES fitness test due to factors such as older age, mobility issues or previous cardiorespiratory disease resulted in a younger, healthier and fit sample. With higher VO_2 max values, the discrepancies between the expected and calculated relative intensities at the absolute CPM intensity thresholds and the differences between the new and established CPM intensity threshold values may have been more pronounced.

In conclusion, PA intensity may be under-estimated for all adults at the established CPM intensity thresholds, and even more so for normal weight individuals. Additionally, adults with overweight and obesity may require lower CPM values to reach moderate and vigorous intensities of PA as they tend to have lower levels of cardiorespiratory fitness than normal weight. However, when cardiorespiratory fitness levels were accounted for, estimated durations of objectively measured MVPA were even shorter than previously thought for individuals across all BMI categories. Thus, more research may be necessary to validate prediction equations and improve the use of accelerometers for assessing the impact of volume of PA participation in a population.

Table 1: Participant characteristics by body mass index category and sex

BMI Category	**Normal Weight**		**Overweight**		**Obesity**	
Sex	**Men**	**Women**	**Men**	**Women**	**Men**	**Women**
Sample size (n)	167	178	160	102	118	103
Age (years)	30.2 ± 0.9	32.3 ± 0.8	35.2 ± 0.9‡	37.0 ± 1.3‡	35.6 ± 0.6‡	34.6 ± 0.9
BMI (kg/m^2)	22.8 ± 0.2	22.0 ± 0.1†	27.5 ± 0.1‡	27.3 ± 0.1‡	33.8 ± 0.3‡*	35.4 ± 0.6†‡*
VO_2 max ($mL \cdot kg^{-1} \cdot min^{-1}$)***	45.3 ± 0.9	37.3 ± 0.8†	41.1 ± 0.7‡	33.8 ± 0.7†‡	39.6 ± 0.7‡	34.6 ± 0.9†‡

Values are presented as Mean ± SE.
† Different from men within BMI group (P<0.05)
‡ Different from Normal weight group (P<0.05)
*Different from Overweight group (P<0.05)
***Estimated VO_2 max

Table 2: Durations of self-report and accelerometer measured MVPA using established and adjusted CPM intensity thresholds by body mass index category and sex

BMI Category	**Normal Weight**		**Overweight**		**Obesity**	
Sex	**Men** (n=167)	**Women** (n=178)	**Men** (n=160)	**Women** (n=102)	**Men** (n=118)	**Women** (n=103)
Durations of MVPA (min/day)						
Self-Report	66.1 ± 5.7	58.9 ± 4.4	70.4 ± 10.8	50.2. ± 10.0	57.6 ± 10.2	41.7 ± 4.2‡
Established CPM thresholds	14.0 ± 1.6	10.4 ± 1.8†	11.7 ± 1.7	8.2 ± 6.0	6.0 ± 1.1‡*	2.9 ± 0.7†‡*
Yngve- Adjusted CPM thresholds	1.5 ± 0.4	4.0 ± 0.8†	2.7 ± 1.2	3.3 ± 1.0	0.6 ± 0.2	0.5 ± 0.3‡*
Swartz- Adjusted CPM thresholds	4.5 ± 0.8	8.8 ± 1.5†	5.8 ± 1.6	8.8 ± 1.4	3.0 ± 0.8	3.2 ± 0.7‡*
Hendelman- Adjusted CPM thresholds	1.4 ± 0.4	4.2 ± 0.8†	2.6 ± 1.2	3.9 ± 1.2	0.6 ± 0.2	0.6 ± 0.3‡*
Freedson- Adjusted CPM thresholds	2.4 ± 0.6	5.4 ± 1.1†	3.8 ± 1.5	5.2 ± 1.2	1.0 ± 0.3‡	1.1 ± 0.4‡*

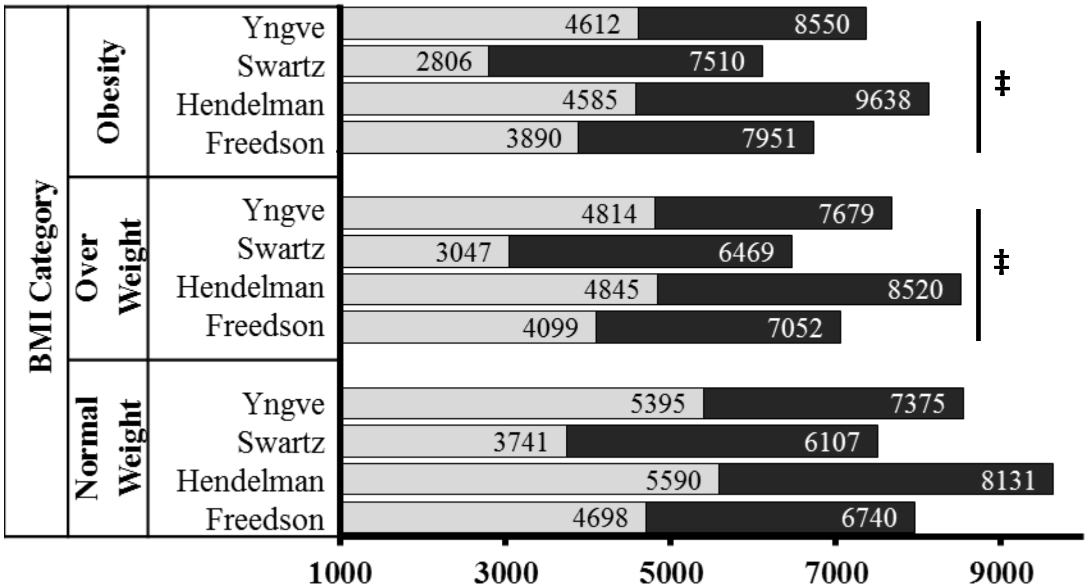
Values are presented as Mean ± SE.
† Different from men within BMI group (P<0.05)
‡ Different from Normal weight group (P<0.05)
* Different from Overweight group (P<0.05)

Table 3: Percent VO_2 max corresponding to the established accelerometer intensity thresholds of 2020 and 5999 CPM by body mass index category and sex

BMI Category	**Normal Weight**		**Overweight**		**Obesity**	
Sex	**Males** (n=167)	**Females** (n=178)	**Males** (n=160)	**Females** (n=102)	**Males** (n=118)	**Females** (n=103)
%VO_2 at 2020 CPM						
Yngve	14.0 ± 0.3	17.1 ± 0.3†	15.3 ± 0.2†	18.7 ± 0.4†‡	15.9 ± 0.3‡	18.3 ± 0.5†‡
Swartz	13.7 ± 0.2	16.3 ± 0.2†	14.8 ± 0.2†	17.6 ± 0.3†‡	15.3 ± 0.2‡	17.3 ± 0.4†‡
Hendelman	11.9 ± 0.2	14.3 ± 0.2†	12.9 ± 0.2†	15.6 ± 0.3†‡	13.4 ± 0.2‡	15.3 ± 0.4†‡
Freedson	14.3 ± 0.3	17.3 ± 0.2†	15.5 ± 0.2†	18.8 ± 0.4†‡	16.1 ± 0.3‡	18.5 ± 0.5†‡
%VO_2 at 5999 CPM						
Yngve	40.1 ± 0.8	49.8 ± 0.7†	43.8 ± 0.7†	54.0 ± 1.2†‡	45.7 ± 0.8‡	53.0 ± 1.4†‡
Swartz	35.5 ± 0.7	43.2 ± 0.6†	38.7 ± 0.6†	47.2 ± 1.0†‡	40.3 ± 0.7‡	46.3 ± 1.2†‡
Hendelman	32.2 ± 0.6	39.4 ± 0.6†	35.2 ± 0.5†	43.1 ± 0.9†‡	36.7 ± 0.6‡	42.3 ± 1.1†‡
Freedson	39.6 ± 0.8	48.4 ± 0.7†	43.2 ± 0.6†	53.1 ± 1.1†‡	45.1 ± 0.8‡	52.1 ± 1.3†‡

Values are presented as Mean ± SE.
† Different from men within BMI group (P<0.05)
‡ Different from normal weight group (P<0.05)
*Different from overweight group (P<0.05)

Men



Women

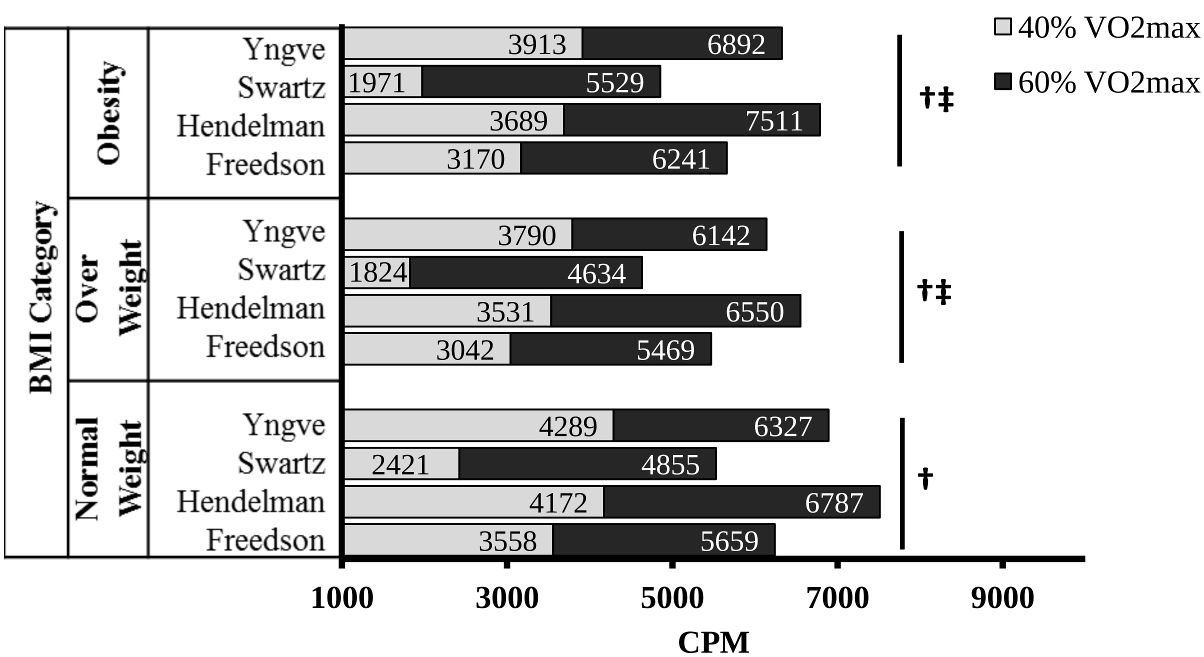


Figure 1. Accelerometer CPM values corresponding to 40 and 60% VO_2 max by sex and body mass index category

† Different from men within BMI group (P<0.05)
‡ Different from normal weight group (P<0.05)

5.0 GENERAL DISCUSSION

The accurate measurement and assessment of PA volume has important implications for health research. As accelerometers are becoming more widely used for assessing PA in population studies and interventions, it is important to apply accelerometer intensity thresholds that will be appropriate for populations across a wide range of characteristics. While there are technological advancements that have improved the ways in which movement or accelerations are captured with accelerometers, there are still challenges and little consensus regarding the methodology used to estimate PA volume at various intensities (94,95). PA volume can also be captured using self-report, but may be subject to bias. Despite the differences between accelerometers and self-report, these measures are often compared (29), with the discrepancies between the two measures being most commonly attributed to errors in self-report (63). However, our studies highlight the possibility that the discrepancies observed may be due to the measurement error of accelerometers.

Established accelerometer intensity thresholds are meant to correspond to various absolute PA intensities. However, factors such as sex and physical fitness, which affect the individual relative intensity of PA at an absolute level of PA, will not be captured by accelerometers. Thus, the application of accelerometer intensity thresholds that are validated with relatively small samples consisting of generally young and healthy adults may not be generalizable for individuals with overweight and obesity, or those with lower levels of physical fitness.

The first manuscript of this thesis demonstrated that at the established accelerometer intensity thresholds, individuals with overweight and obesity will have higher EE rates and lower measured durations of MVPA compared to individuals with normal weight. As individuals with overweight and obesity required lower accelerometer values to reach a similar EE rate as individuals with normal weight, adjusting the intensity thresholds to account for body mass resulted in longer durations of measured MVPA for individuals with overweight and obesity. However, even with the use of adjusted intensity thresholds, durations of MVPA generally remained shorter than durations of self-report within all BMI categories.

The second manuscript of this thesis demonstrated that the established accelerometer moderate and vigorous intensity thresholds may correspond to lower relative intensities of PA than expected after accounting for cardiorespiratory levels of fitness in the United States population. Interestingly, the established intensity thresholds were the most under-estimated for individuals with normal weight, and after adjusting the intensity thresholds to correspond to common definitions of moderate (40% VO_2 max) and vigorous (60% VO_2 max) intensity, durations of objective measured PA were even shorter than those measured using the established accelerometer intensity thresholds. Therefore, the discrepancies between objective and subjective measures of PA were magnified after accounting for cardiorespiratory fitness.

In conclusion, the magnitude of discrepancies between accelerometer measured and self-report durations of PA were reduced for individuals with overweight and obesity when accounting body mass and cardiorespiratory fitness. The findings from these studies demonstrate that the current accelerometer intensity thresholds may not be representative of the PA intensity that they describe, which may contribute to the measurement error of accelerometers within a population. As such, accounting for these and other factors that may influence the relative intensity of PA when applying accelerometer intensity thresholds to estimate durations of PA may be important for improving the measurement of PA volume using accelerometers within a population.

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